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Offset of rotation centers creates a bias in isokinetics: A virtual model including stiffness or friction

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Abstract

The present paper deals with a virtual model devoted to isokinetics and isometrics assessment of a human muscular group in the common joints, knee, ankle, hip, shoulder, cervical spine, etc. This virtual model with an analytical analysis followed by a numerical simulation is able to predict measurement errors of the joint torque due to offset of rotation centers between the body segment and the ergometer arm. As soon as offset is present, errors increase due to the influence of inertial effects, gravity effects, stiffness due to the limb strapping on the ergometer arm or Coulomb friction between limb and ergometer. The analytical model is written in terms of Lagrange formalism and the numerical model uses ADAMS software adapted to multi-body dynamics simulations. Results of models show a maximal relative error of 11%, for a 10% relative offset between the rotation centers. Inertial contributions are found to be negligible but gravity effects must be discussed in regard to the measured torque. Stiffness or friction effects may also increase the torque error; in particular when offset occurs, it is shown that errors due to friction have to be considered for all torque level while only stiffness effects have to be considered for torque less than 25 N m. This study also emphasizes the influence of the angular range of motion at a given angular position.

Keywords: Isokinetics; Isometrics; Assessment; Stiffness; Friction

1. Introduction

Kinematics of human joints is essential in orthopaedics, rehabilitation medicine (Woltring et al., 1985) and also in biomechanical motion analysis (Chang and Pollard, 2006; Halvorsen et al., 1999). This analysis must be completed by joint forces and direct torque measurements (Begon et al., 2006). Thus the need for specific mechanical apparatus is unavoidable. A single arm ergometer can be used for such purposes; it gives access to the two main types of exercises: isokinetics and isometrics. In both cases, the ergometer must deliver force or torque value with absolute precision.

An isokinetic exercise is based on a forced movement of a limb with constant angular velocity. Whether the muscle group acting on the limb drives the ergometer (concentric contraction) or is driven by the ergometer (eccentric contraction) is of no importance. The constant velocity is obtained by a digitally controlled servo-motor. Isometric or isokinetic measurements on joints such as knee (Manou et al., 2002), ankle (Gleeson and Mercer, 1992), or cervical spine (Portero and Genriès, 2003; Olivier and Du Toit, 2008) are used for the assessment of muscular capacity or muscular fatigue. However, for isometrics or isokinetics, authors strongly insist on influence of experimental clinical procedures such as subject position (Falkel et al., 1987; Hageman et al., 1989; Miller et al., 1997), gravity (Winter et al., 1981), inter-experimentalist, inter-ergometer, inter-test or inter-subject reproducibility (Mayer et al., 1994), inertial effects (Lossifidou and Baltzopoulos, 1998) and also alignment of joint and ergometer axis (Sorensen et al., 1998; Rothstein et al., 1987). This last point is generally underlined and is the object of a repeated recommendation. To our knowledge, only one theoretical study (Reimann et al., 1997) was published earlier though

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Nomenclature

C_e	torque measured by the ergometer
C_m	torque produced by the muscular group at the joint
T	ratio between measured and muscle torque or correction factor ($T = -C_e/C_m$)
α	rotation angle of the ergometer arm
α_0	initial rotation angle of the ergometer arm
$\dot{\alpha}$	angular velocity of ergometer arm (constant)
β	rotation angle of the limb
$\dot{\beta}$	angular velocity of limb (variable)
V	ratio between limb and ergometer arm velocity ($V = \dot{\beta}/\dot{\alpha}$)
d	offset distance between ergometer rotation center and limb rotation center
φ	offset angular position
G_m	limb center of mass
G_e	ergometer arm center of mass
l_{Gm}	distance between joint rotation center and limb center of mass
l_{Ge}	distance between joint rotation center and ergometer arm center of mass
l_m	length of the limb (variable)
l_e	length of the ergometer arm (constant)
I_m	limb inertia (proximal)
I_e	ergometer arm inertia (with respect to rotation axis)
m_m	limb mass
m_e	ergometer arm mass
E	relative error defined by $E = d/l_e$
f	Coulomb friction coefficient
k	stiffness due to strapping
c	viscous damping associated to stiffness
O_e	ergometer rotation center
O_m	joint rotation center
ROM	range of motion
α_P, α_{P1}, α_{P2}, α_{P3}	initial angular positions of the ergometer arm for different ROM

in fact this paper was based on observations and measurements. However, these authors presented the influence of rotation center offset on measured torque, angle and angular velocity. In particular, they showed that a 10% relative error of axis misalignment can lead to a 10% torque relative error.

In general, the articular joint axis and the ergometer axis may be situated anywhere. The torque component is measured in the direction of the ergometer axis. The misalignment of axes is then reduced to an offset between rotation centers of limb and rotation center of ergometer. In many types of joints, this offset varies in distance and direction, the evaluation of which is not practicable. Therefore, the hypothesis of a constant offset is proposed here. The goal of the present paper is to show with a virtual model that the main source of measurement errors comes from this offset. Only when offset occurs do additional errors originate from other parameters: inertial effects, gravity effects, strapping stiffness mainly originating from flesh movements on the limb bone or friction between the limb and the ergometer arm. These last two effects are considered as mutually exclusive.

In practice, it may be difficult to reduce the offset to zero. Moreover, it happens that the rotation center of the joint moves during the exercise, the knee for example, thus preventing the offset zeroing. Anyhow, in the case of variable rotation center for the limb, limb movement is necessary otherwise the limb may be damaged.

The interest of the paper is to propose methods to identify correction factors taken into account the different relevant parameters such as inertia, gravity, strapping stiffness or friction between limb and ergometer arm in the presence of an offset. This model could also be used to alert isokinetics users to the importance of considering the relevant parameters. If relative results are expected, raw data are sufficient, but, for asolute and accurate results, a correction factor must be introduced.

2. Methods

2.1. Analytical model of offset

The proposed virtual model can be applied to any human joint. In Fig. 1, we show two examples of ergometer arm and limb misalignment for the elbow or the knee. In this paper, the parametric description of the model is based on the knee. Fig. 2 shows the mechanical variables and parameters necessary to write the mechanics equations that permit the expression of the ratio T between the ergometer measured torque C_e and the torque C_m produced by the joint muscles. In the paper, this ratio is also known as torque correction factor.

In the Lagrange formalism, we express kinetic energy E_c, potential energy E_p restricted to gravity and power P of efforts,

$$E_c = \tfrac{1}{2} I_m \dot{\beta}^2 + \tfrac{1}{2} I_e \dot{\alpha}^2 \quad (1)$$

$$E_p = -m_m g (l_{Gm} \sin\beta + d \sin\varphi) - m_e g l_{Ge} \sin\alpha \quad (2)$$

$$P = C_e \dot{\alpha} + C_m \dot{\beta} \quad (3)$$

The angles α and β are not independent. At the velocity level their dependence is written through a linear relationship,

$$V\dot{\alpha} - \dot{\beta} = 0 \quad (4)$$

which can be written as

$$A\dot{q} = 0 \quad \text{with } \dot{q} = \begin{bmatrix} \dot{\alpha} \\ \dot{\beta} \end{bmatrix}, \; A = \begin{bmatrix} V & -1 \end{bmatrix} \quad (5)$$

Since the generalized coordinates α and β are dependent, we introduce a Lagrange multiplier λ. Denoting the power coefficients by Q, the Lagrange equations are the following:

$$\frac{d}{dt}\frac{\partial E_c}{\partial \dot{q}} - \frac{\partial E_c}{\partial q} = Q - \frac{\partial E_p}{\partial q} + A^t \lambda \quad (6)$$

where q is the vector of generalized coordinates.